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MEETING PAPER

Mechanical Behavior of Sealed SPR Caverns

by

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1994 Spring Meeting
April 25-27
Houston, Texas

ABSTRACT

It is inevitable that sealing and abandonment will someday occur in a U.S. Strategic Petroleum Reserve (SPR) cavern or caverns. To gain insight into the long-term behavior of a typical SPR cavern following sealing and abandonment, a suite of finite element analyses were performed. The analyses predict how quickly and to what extent a cavern pressurizes after it is plugged. The analyses examine the stability of the cavern as it changes shape due to the increased pressures generated after plugging. Internal fluid pressures in a brine filled cavern eventually exceed lithostatic pressure in the upper portion of the cavern resulting in enlargement and stress reduction. The buildup of fluid pressure after plugging is largely determined by salt creep, salt dissolution, and geothermal heating of brine. Volumetric closure due to creep increases brine pressure. Salt dissolution and geothermal heating occur when the brine is unsaturated and cooler than the surrounding salt at the time of plugging. The individual and coupled effects of creep, dissolution, and geothermal heating are modeled. The analyses suggest that the predicted rate and magnitude of fluid pressurization in SPR caverns is not high enough to result in fracturing of the salt. However, cavern pressure can be substantially mitigated by delaying plugging until the brine has come closer to thermal equilibrium.

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It is inevitable that sealing and abandonment will someday occur in a U.S. Strategic Petroleum Reserve (SPR) cavern or caverns. To gain insight into the long-term behavior of a typical SPR cavern following sealing and abandonment, a suite of finite element analyses were performed. The analyses predict how quickly and to what extent a cavern pressurizes after it is plugged. The analyses examine the stability of the cavern as it changes shape due to the increased pressures generated after plugging. Internal fluid pressures in a brine filled cavern eventually exceed lithostatic pressure in the upper portion of the cavern resulting in enlargement and stress reduction. The buildup of fluid pressure after plugging is largely determined by salt creep, salt dissolution, and geothermal heating of brine. Volumetric closure due to creep increases brine pressure. Salt dissolution and geothermal heating occur when the brine is unsaturated and cooler than the surrounding salt at the time of plugging. The individual and coupled effects of creep, dissolution, and geothermal heating are modeled. The analyses suggest that the predicted rate and magnitude of fluid pressurization in SPR caverns is not high enough to result in fracturing of the salt. However, cavern pressure can be substantially mitigated by delaying plugging until the brine has come closer to thermal equilibrium.

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Introduction

The Strategic Petroleum Reserve (SPR) was created to reduce the vulnerability of the United States to interruptions by foreign oil suppliers. Approximately 600 million barrels of crude oil are presently stored underground in salt domes at five sites located along the Gulf of Mexico. One underground mine and approximately 60 leached caverns are used to store the oil.

It is inevitable that plugging and abandonment will someday occur in an SPR cavern or caverns. A simplistic view of a plugged SPR cavern is shown in Figure 1. To gain insight into the long-term behavior following plugging, a series of mechanical finite-element analyses were performed. The analyses predict how quickly and to what extent the brine in a cavern pressurizes after it is plugged. The analyses examine the stability of the cavern as its changes shape due to the excessive pressures generated due to salt creep and geothermal heating of the brine in the cavern. The effect of salt dissolution on cavern pressure, due to displacing cavern oil with freshwater prior to plugging, is also quantified.

The factors that influence brine pressure in a sealed cavern-- salt creep, brine temperature changes, and salt dissolution--are briefly discussed below.

Cavern Pressure After Sealing

Creep is an ongoing process that continues long after a cavern is sealed, perhaps as long as the cavern has a vertical dimension. As a result of differences in density between brine and salt, a differential pressure gradient (and hence creep) will exist between the brine and salt. Fully saturated brine has a density that results in a pressure gradient of approximately 0.52 psi/ft of depth, whereas salt has a pressure gradient of approximately 0.94 psi/ft of depth. This results in a pressure differential of 0.42 psi per ft of depth. Volumetric closure due to creep will cause the brine pressure to increase with time. At some point however, the brine pressure in the upper portion of the cavern is expected to exceed lithostatic stress and the top portion of the cavern will expand. When the rate of volumetric expansion in the upper portion of the cavern approaches that of contraction in the lower portion of the cavern, the rate of brine pressurization will approach zero and the cavern brine pressure is assumed to reach equilibrium. This pressure state is illustrated in

Figure 2. This definition of equilibrium will suffice for purposes of this report because appreciable changes are not predicted in the vertical dimension of a sealed cavern within the time frame evaluated here (up to 1000 years). However, as alluded to above, geologic time scales will permit the cavern to completely close at the bottom, thereby changing the equilibrium pressure as the bottom depth of the cavern is redefined.

Brine temperature changes result from the heat exchange between the salt in the cavern walls and cavern brine. Prior to plugging and abandonment, fresh water or brine will be injected into the caverns to remove the oil. Because the injected fluid temperature at plugging is typically less than the cavern walls, heating of the fluid will attempt to expand the brine which results in a pressure buildup over time. Pressurization due to geothermal heat exchange will slow as the average brine temperature approaches the average salt temperature. If unsaturated brine is injected into a cavern, the solutioning that occurs is endothermic resulting in a temperature drop up to 5 °F. Thereafter, the fluid heats until thermal equilibrium is reached with the salt. The heat transfer mechanisms and thermal modeling associated with SPR caverns are discussed by Tomasko (1985).

Salt dissolution will occur as a consequence of injecting fresh water or partially saturated brine into cavern during removal of oil. Even if the brine were fully saturated when injected, its heating due to contact with the cavern walls would allow an increase in the solute content of the brine and therefore some dissolution. Salt dissolution creates additional cavern space and brine volume. However, the volume leached is slightly greater than the increase in brine volume that occurs. This will result in a decrease in the brine pressure. From a chemistry viewpoint, the bonding between the water molecules and the sodium-chloride ions results in a solution volume that is approximately 3.2 % smaller than the total volumes of the constituents. The net decrease in volume results in an decrease in pressure according to the compressibility factor of the brine. Because brine saturation is a function of temperature and pressure, the salinity will to a small extent dependent upon the thermal exchanges and creep.

Perhaps the most significant factor controlling fluid pressure in an abandoned cavern is the ability of the cavern to remain fluid tight or sealed. A leak path could form when the fluid pressure in the cavern exceeds the lithostatic pressure of the salt. This pressure condition occurs in the upper portion of the cavern (see Figure 2) and the pressure differential will be greatest at the plugged casing seat. If material interfaces separate and a leak path is formed at the casing seat of an access well, it may progress upwards with time along the salt/casing interface because the pressure difference between the brine and salt increases with elevation. In addition, under rapid pressure rates, the salt itself may fracture and form a leak path (Gniady and Ehgartner, 1993). A leak path can also form at pressures below lithostatic if the sealing materials have become degraded. Conventional materials (salt saturated, Class H cement) used in the plugging of cavern access wells, in addition to the steel casings and cemented annulus, can degrade with time. This could increase the permeability in and between the materials to eventually establish a leak path and thus reduce cavern pressures below that predicted for a sealed cavern. A more effective long-term seal may be achieved using carefully selected materials for sealing. A natural substance, such as bitumen or salt itself, may provide the long-term compatibility and low permeability needed to permanently seal caverns. Supplemental strategies such as adding a viscous capping fluid to the cavern could prevent or retard fluid migration by capillary action and increasing frictional resistance during flow. These topics are outside the scope of this analysis report, but should be considered in the plugging and abandonment plan of a cavern. The analyses in this report assume that the cavern remains sealed over the simulation period.

Finite-Element Model

Cavern behavior was simulated for 1000 years to capture the long-term response of a sealed cavern. The baseline finite-element model used for the initial 30 years of simulation is described in detail by Ehgartner (1992). The model is intended to represent a typical SPR cavern field. Basically, the cavern field consists of a network of 2000 ft high by 170 ft diameter caverns spaced at 750 ft (center-to-center). The top of the cylindrical shaped caverns is at a depth of 2500 ft below the ground surface and 500 ft into the salt. The salt is overlaid with 400 ft of caprock (typ. anhydrite) and 1600 ft of overburden (typ. sand). The casing seat was assumed to be located 100 ft above the roof of the cavern. At the casing seat depth (2400 ft), the lithostatic pressure was estimated as 2110 psi, based on the lithology and brine pressure is assumed to be 1250 psi at the time of plugging, based on the density of brine to the surface (0.52 psi/ft) and no additional wellhead pressure. The casing seat and the open uncased wellbore between the casing seat and cavern were not modeled in the calculations as their relatively small volume will have a minor effect on the overall pressurization rates for the cavern.

The cavern was simulated as filled with oil for the first 30 years. A depth-dependent pressure gradient was applied to the cavern boundary to account for the weight of the oil and an average operational oil pressure of 680 psi at the wellhead. An oil pressure of 680 psi is typical and represents an oil/brine interface at the bottom of the cavern with no brine pressure at the surface.

After 30 years, a complete withdrawal of oil from the cavern was simulated. The oil pressure boundary was replaced with brine pressure equivalent to 0 psi at the wellhead. The pressure change was simulated as occurring instantaneously, whereas in reality it will take approximately 0.29 years to replace the cavern oil with brine. At 30.29 years, the cavern is instantaneously plugged and brine response was simulated using special fluid elements. The brine elements modeled a compressible, inviscid fluid with a bulk modulus of 3.46×10^5 psi and density of 1.20 g/cc which remained constant throughout the analysis. The finite-element mesh is shown in Figure 3-- before and after emplacement of the special fluid elements at 30.29 years. The two-dimensional axisymmetric analyses rotate the mesh about the cavern centerline and constrain radial displacements on the outer edge of the mesh (rollered boundary conditions) to approximate an infinite number of caverns in a field.

The M-D constitutive model (Munson, Fossum, and Senseny, 1989) was used to simulate the mechanical behavior of the salt in the SPECTROM-32 finite-element code (Callahan, Fossum, and Svalstad, 1989). Salt properties are partially based on triaxial compressive and creep tests of West Hackberry salt (Wawersik and Zeuch, 1984). The predicted results of the baseline model closely agreed with measured surface subsidence and cavern pressurization rates at West Hackberry thus providing some verification and credibility to the model. However, the analyses in this report are limited in that they are purely mechanical and do not simulate fluid flow. To do so would require as a minimum a coupled mechanical-hydrological model (and properties) for salt that contains the appropriate deformational and fluid flow mechanisms. At this time, such models are more an area of research than of application.

Geothermal heating was simulated by assigning a prescribed temperature history to the brine. For this purpose, the average oil temperatures measured at Bryan Mound and fitted to a general expression by Todd (1991) was used. The following temperature history was assigned to the brine after plugging of the cavern:

$$T = T_\infty - (T_\infty - T_o)e^{-t/t}$$

where T is the time dependent temperature(°F), T_∞ is the final temperature at equilibrium (124 °F), T_o is the initial temperature(107 °F), t is the time (yrs) after cavern plugging, and t is a constant(6.6 yrs). T_∞ represents the in situ temperature of salt at a depth of 3500 ft (cavern mid-height). The thermal expansion of brine was assumed to be constant at 1.54 E-4 1/°F and salt temperatures were not changed in the finite-element model. In reality the local salt temperatures will slightly decrease due to the heat exchange with brine.

Salt dissolution was simulated by assigning an equivalent temperature drop to the brine based on the net volumetric change of the cavern and brine (normalized to cavern volume) divided by the thermal expansion of brine. As discussed earlier, dissolutioning creates slightly more cavern volume than brine volume. This approach is artificial because brine temperatures are reduced in the model to account for volume reductions. Salt temperatures remain unchanged. This approach enables the dissolution response to be simulated without actually replacing salt elements in the model with brine elements and imposing a reduced pressure on them. However, the cavern geometry in the model is unchanged by the dissolutioning. The average increase in cavern diameter after a complete withdrawal of oil is less than 10 %. This small change in the shape of the cavern is assumed to have a negligible effect on brine pressurization in the cavern. SANSMIC (Russo, 1983) was used to calculate the net volume change due to dissolution following a complete withdrawal (Kuhlman and Russo, 1992). In this calculation, fresh water was injected into a typical SPR cavern. The drawdown of oil was completed in 106 days (0.29 yrs) and dissolution continued for a additional 120 days (0.33 yrs) after the drawdown. In this paper, the cavern is plugged immediately following oil withdrawal (30.29 yrs) to maximize the pressure drop due to dissolutioning. Changes in salinity due to changes in brine temperature and pressure were assumed to be negligible.

Results

Figure 4 shows the effect of creep and salt dissolution on brine pressure at the casing seat after plugging of the casing. For comparative purposes, the initial brine pressure at the time of plugging is shown. The upper curve in the Figure represents the response of the cavern fluid to creep. When only creep is considered (no dissolution), the cavern pressurizes after sealing. The effect of including dissolution was to initially lower pressures after sealing (see lower curve). Dissolution after cavern sealing resulted in a depressurization of approximately 700 psi within 1 month. At one month after cavern sealing, the rate of volumetric decrease due to leaching approximately equals the volumetric closure rate due to creep. Thereafter, creep dominates the volumetric response of the cavern resulting in a pressure increase. The pressure difference between the creep and creep-dissolution models amounts to approximately 700 psi at the end of the 120 day dissolution period.

Figure 5 shows the effect of geothermal heating on the brine pressure in a sealed cavern. The lithostatic pressure at the casing seat and the predicted response of modeling only creep are also shown. Geothermal heating of brine results in pressures in excess of lithostatic at the casing seat within 2.1 years after sealing. The predicted thermal pressure peaks at about 15 years after increasing over 1800 psi from the initial 1250 psi brine pressure at the casing seat. The rate of pressure increase during this time decreases, thus implying that the creep response of the salt is more able to accommodate the geothermal expansion of brine as heat exchange of salt with brine decreases with time. At later times, brine pressures decrease as the net cavern volume adjusts by creep (enlargement). Pressure contributions due to geothermal heating are small at this time. In contrast the creep only model predicts relatively modest pressure increases.

Figure 6 shows cavern deformations (magnified by 3) and salt velocity vectors at three different times for the heated brine analysis. A velocity vector indicates the direction of salt flow and relative particle velocity at a particular time. Prior to plugging, the salt flow is predominantly downward and into the lower portion of the cavern where the majority of deformation is predicted and closure is predicted at all locations in the cavern. Several years after plugging, the cavern walls are expanding because the cavern fluid pressures are greater than the stresses in the salt. At later times, the cavern responds by establishing the long-term behavior where closure occurs in the bottom portion of the cavern, and expansion in the upper portion.

Although the caverns are predicted to experience deformational changes after plugging, the amount is small. For the heated brine analysis, the roof at 1000 years laterally expanded less than 0.7 ft and vertical uplift at the center of the roof is predicted to be only 1.1 ft accompanied by some local uplift at the surface. Near the bottom of the cavern, closure is drastically slowed as brine pressures increase after plugging. The additional strain accumulation in the salt is less than 1 percent during the 1000 years after plugging of the cavern. This is small compared to the estimated 15 percent strain that is typically required to fail salt under this stress state (Preece and Wawersik, 1984). The maximum amount of surface subsidence is predicted for the case where dissolution occurs following plugging and no geothermal heating of brine occurs. The relatively lower cavern pressures for this case result in approximately 1 ft of additional surface subsidence after 1000 years following plugging.

To further evaluate the stability of the cavern, the stresses in the salt were examined, particularly during the relatively rapid cavern enlargement period following plugging in the heated brine analysis. Of concern was the potential development of tensile stresses in the roof or walls of the cavern as the cavern enlarges. No tensile stresses were predicted in the salt at any time. However, the compressive stresses in the salt adjacent to the cavern decreased as the cavern initially enlarged. The minimum compressive stresses in the roof and walls in the upper portion of the cavern were 1760 psi and 1605 psi, respectively at approximately 2.5 years after plugging. Thereafter, the roof and wall stresses became more compressive with time and remained slightly below brine pressures through the remainder of the analysis.

Figures 7 and 8 shows the brine pressure predictions for the creep, creep-thermal, creep-dissolution, and creep-dissolution-thermal models out to 50 and 1000 years, respectively. The thermal effect is most significant as noted by the separation between the thermal (upper two curves) and non-thermal (lower two curves) results. Dissolution is a secondary effect which results in an initial decrease in pressure for both thermal or non-thermal models. Later times show dissolution to result in a higher brine pressure for the thermal model and a lower pressure for the constant temperature model. Table 1 lists the predicted time to exceed lithostatic stress at the casing seat.

The thermal heating of the brine results in approximately a 100-fold decrease in the time to reach lithostatic pressure at the casing seat, whereas dissolution of salt following plugging results in approximately a 2-fold increase in the time to lithostatic pressure. The geothermal heating of brine not only results in a quicker time to exceed lithostatic pressure, but the peak pressures are much greater for the thermal models.

Table 1

Predicted Time for Brine Pressure to Reach Lithostatic At Casing Seat

Model	Time to Lithostatic (yrs)
salt creep--geothermal heating of brine	2.1
salt creep--salt dissolution--geothermal heating of brine	3.8
salt creep	206
salt creep--salt dissolution	352

CONCLUSIONS

The sealed cavern analyses show that after plugging of the cavern, brine pressures at the casing seat are sensitive to the initial temperature and salinity of the brine in the cavern. The geothermal heating of brine had the greatest influence on brine pressures after sealing. The predicted time for geothermally heated brine to reach lithostatic pressure at the casing seat was only a couple of years after plugging. In contrast, if geothermal heating of brine did not occur, two hundred years of cavern creep was required to pressurize the brine above lithostatic pressure at the casing seat. The maximum predicted brine pressures and pressurization rates were much larger for geothermally heated brine. These results assume no salt dissolution after plugging of the cavern. When salt dissolution is included in the analyses, the time required to reach lithostatic pressure at the casing seat was nearly doubled.

Examination of the stress state surrounding the cavern showed the stresses in the salt to remain compressive after plugging. The worse condition was for the heated brine case which resulted in a relatively rapid pressurization of the brine in the cavern. The minimum compressive stress predicted in the salt was approximately 70 percent of lithostatic. After reducing in magnitude, the minimum compressive stress eventually became more compressive with time. Cavern deformation or creep rates are reduced after sealing due to the increased cavern brine pressures. The accumulated salt strain increased less than 1 percent over a 1000 year period after sealing due to small roof and wall displacements. The stresses and strains in the salt indicate that the cavern would be mechanically stable after plugging.

The sensitivity of cavern brine pressures to thermal and dissolution effects provides an opportunity to engineer cavern plugging and abandonment procedures that could significantly 1) increase the time before the casing seat exceeds lithostatic pressure and 2) decrease the maximum fluid pressure exerted on the plugged casing seat. Higher brine temperatures and lower salinities at the time a cavern is plugged results in a sealing advantages in that cavern pressures and pressurization rates are reduced, particularly during the early stages of abandonment. As discussed earlier, the potential for a leak is significantly increased when pressures above lithostatic are reached, particularly for rapid pressurization rates. Increasing the brine temperature to the average in situ temperature of the cavern can eliminate the subsequent natural thermal-pressure increase of the brine after plugging the cavern. A higher brine temperature may be obtained naturally by delaying installation of the plug and thus allowing the salt to heat the brine, or by artificially pre-heating the injected brine during oil withdrawal. The delay tactic, may be most economical, but would remove the advantage due to dissolution.

In conclusion, the long-term sealing analyses suggest that the predicted rate of brine pressurization is not high enough to result in fracturing of the salt. The analyses also show that the brine pressurization rate can be substantially mitigated by delaying plugging until the brine has come closer to thermal equilibrium.

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INSERT FIGURES 1 THROUGH 8